

Digital signal processing for a thermal neutron detector using ZnS(Ag):⁶LiF scintillating layers read out with WLS fibers and SiPMs

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Abstract

We present a digital signal processing system based on a photon counting approach which we developed for a thermal neutron detector consisting of ZnS(Ag):⁶LiF scintillating layers read out with WLS fibers and SiPMs. Three digital filters have been evaluated: a moving sum, a moving sum after differentiation and a digital CR-RC⁴ filter. The performances of the detector with these filters are presented. A full analog signal processing using a CR-RC⁴ filter has been emulated digitally. The detector performance obtained with this analog approach is compared with the one obtained with the best performing digital approach.

Keywords: Digital signal processing, FIR filters, Thermal neutron detector, ZnS:⁶LiF scintillator, Silicon photomultiplier (SiPM)

1. Introduction

A 1-D position sensitive detector for thermal neutrons is currently under development [1, 2, 3] for upgrading the POLDI instrument, a strain-scanning diffractometer installed at the Swiss neutron spallation source (SINQ) at PSI. This detector is based on ZnS(Ag):⁶LiF scintillating layers read out with wavelength shifting fibers (WLS) and silicon photomultipliers (SiPM).

The main challenges concerning the signal processing are the reduction of the detector background count rate due to the SiPM dark counts down to 10⁻³ Hz and the reduction of the multi-count ratio due to the scintillator afterglow down to 10⁻³, together with a high trigger efficiency and a high neutron count rate capability.

2. Principle of the signal processing system (SPS)

Figure 1 shows the block diagram of the SPS. The SiPM signal is amplified and shaped by a wide band-width amplifier. The output of the amplifier is then fed into a fast leading edge discriminator with a threshold set at 0.5 photoelectron. During each consecutive time slice Δt of 400 ns (for example), the number of SD pulses after the discriminator is measured. In other words, the density of SD pulses in time is sampled.

Once sampled, the signal is filtered and the following triggering conditions are ANDed: a) The channel is ready (after each trigger, an artificial dead time is introduced to prevent multiple triggers on the same events). b) The filter output is maximum. c) The filter output is higher than a certain threshold.

The time stamp of an event is defined by the time slice during which the filter output is maximum.

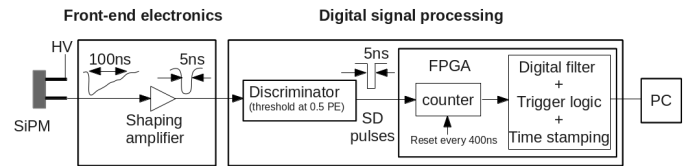


Figure 1: Block diagram of the signal processing system.

3. Digital filters under evaluation

This section presents the discrete-time implementation of the three digital filters which have been evaluated. We denote x_i and z_i the discrete samples of the signal at the input and output of the filter, respectively.

a) Moving sum (MS) of span M $z_i = z_{i-1} + x_i - x_{i-M}$

b) Moving sum after differentiation (DI+MS) $z_i = z_{i-1} + y_i - y_{i-M}$
 $y_i = x_i - x_{i-M}$ (DI)

c) CR-RC⁴ $z_i = \sum_{j=1}^5 b_j z_{i-j} + \sum_{j=1}^4 a_j x_{i-j}$
 where a_j and b_j are non-integer constants involving the time constant RC and the sampling interval Δt [4].

4. Evaluation of the digital filters

The evaluation is based on real data which provide for each detected neutron the temporal sequence of SD pulses produced during the first 80 μ s following the neutron capture. The data file contains 10 kevents. During the measurement, the rate of captured neutrons was 20 Hz and the SiPM dark count rate was 64 kHz. In order to evaluate the filter performances at different SiPM dark count rates, temporal sequences of dark counts are simulated and merged to the measured data. SiPM crosstalk and afterpulses, as well as the saturation of the SD pulse counting due to the 12 ns dead time of the discriminator are implemented in the simulation.

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Figure 2 shows the trigger efficiency as a function of the artificial dead time for the DI+MS filter. The SiPM dark count rate is 63 kHz and the trigger threshold is adjusted for each value of the dead time so that the multi-count ratio is $< 10^{-3}$. For each filter, we determine the minimum dead time which can be set without significant decrease of the trigger efficiency. Table 1 gives these minimum dead times τ for all the evaluated filters as well as the time resolutions R_t (stdev) obtained under the following conditions: SiPM dark count rate of 2 MHz, background count rate $< 10^{-3}$ Hz, multi-count ratio $< 10^{-3}$. The time resolution is approximately constant up to a dark count rate of ~ 20 MHz. Figure 3 shows the trigger efficiency as a function of the SiPM dark count rate for the DI+MS and CR-RC⁴ filters, under the conditions that the background count rate and the multi-count ratio are below 10^{-3} Hz and 10^{-3} , respectively.

Table 1: Dead times τ set for all the evaluated filters and time resolutions R_t under the following conditions: SiPM dark count rate of 2 MHz, background count rate $< 10^{-3}$ Hz, multi-count ratio $< 10^{-3}$.

Filter	M or RC (μ s), Δt (ns)	τ (μ s)	R_t (ns)
MS	5, 200	20	120
	10, 200	40	210
CR-RC ⁴	0.5, 200	5	220
	1, 200	9	360
MS+DI	5, 200	2	75
	5, 400	4	140
	5, 800	8	320
	10, 800	14	650

To estimate the performances of an analog pulse processing, the measured data are corrected for the 12 ns dead time of the discriminator and the effect of the SiPM crosstalk is added. The discrete-time implementation of the CR-RC⁴ filter is then used to emulate an analog readout with a CR-RC⁴ filter. Figure 4 shows the trigger efficiency as a function of the SiPM dark count rate for the digital approach using the DI+MS filter and for a full analog approach using a CR-RC⁴ filter.

5. Conclusion

The MS filter requires a significantly longer dead time than the other filters to ensure a multi-count ratio below 10^{-3} . The DI+MS filter shows the same performance as the digital CR-RC⁴ filter and it requires much less computational resources. We report the following performance parameters of the detector with the DI+MS filter ($M=5$, $\Delta t=400$ ns): trigger efficiency $\geq 80\%$, dead time of 4 μ s, time resolution (stdev) < 170 ns (contribution from the SPS), background count rate $< 10^{-3}$ Hz, multi-count ratio $< 10^{-3}$. All these parameters are achieved up to a SiPM dark count rate of 5 MHz. On the basis of preliminary irradiation measurements, we estimate that an increase of the SiPM dark count rate from the nominal value of 100 kHz to 5 MHz corresponds to more than 20 years of operation.

A full analog signal processing using a CR-RC⁴ filter has been emulated digitally. Up to 5 MHz SiPM dark count rate, the digital signal processing using the DI+MS filter has about the same performance as the full analog signal processing.

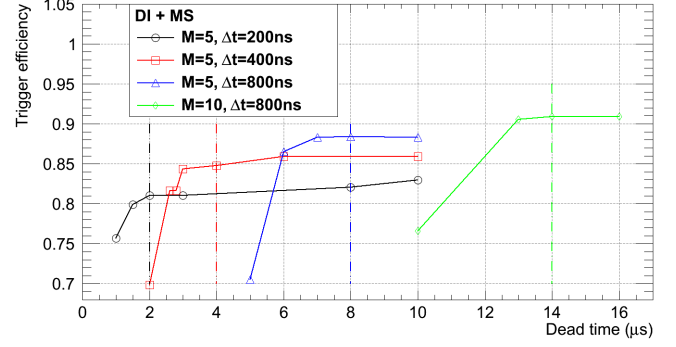


Figure 2: Trigger efficiency versus dead time for the DI+MS filter. The SiPM dark count rate is 63 kHz and the trigger threshold is adjusted to ensure a multi-count ratio $< 10^{-3}$. The vertical dashed lines denote the minimum dead times which can be set without significant decrease of the trigger efficiency.

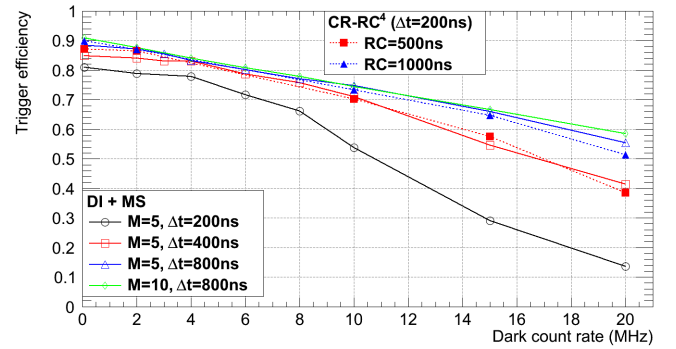


Figure 3: Trigger efficiency versus SiPM dark count rate. Conditions: background count rate $< 10^{-3}$ Hz, multi-count ratio $< 10^{-3}$, dead times given by table 1.

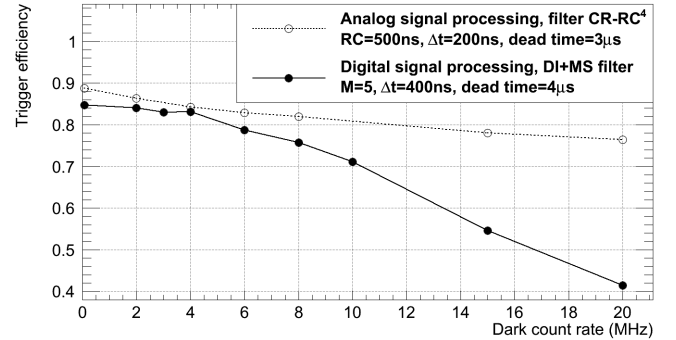


Figure 4: Trigger efficiency versus SiPM dark count rate for a digital approach using the DI+MS filter and for a full analog approach using a CR-RC⁴ filter. Conditions: background count rate $< 10^{-3}$ Hz, multi-count ratio $< 10^{-3}$.

References

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